

# Spectral analysis of extinguished sunlight

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Received December 2002

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## Abstract

SAOZ (Système d'Analyse par Observation Zénitale) is a balloon born experiment which determines the column density of several molecular species from the visible spectrum of sunlight. We will use sequence of spectra collected during a sunset to discuss atmospheric extinction, and the nature of the radiation field in the atmosphere.

The radiation field in the atmosphere is, from daylight to sunset, and with a clear sky, dominated by light coming from the direction of the sun. This light is composed of direct sunlight (extinguished by the gas), and of sunlight forward-scattered by aerosols. As the sun sets, aerosol scattering is first perceived towards the UV. It progressively replaces direct sunlight over all of the spectrum. Our analysis permits fixing the main parameters of each component of the radiation field at any time.

The fits we find for the extinction of sunlight in the atmosphere must also apply to starlight. Thus, the present work can be used in astronomy to correct ground-based spectral observations for extinction in the atmosphere.

*Key words:* atmospheric effects; diffusion; scattering; radiative transfer

*PACS:* 42.68.J, 42.68.A., 94.10.G, 92.60, 03.80, 94.10.L, 92.60.E, 51.20, 95.30.Jx

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## 1 Introduction

SAOZ is a balloon experiment in which the light collected by a wide field conical mirror is analyzed in the visible by two large bandwidth spectrometers. The original aim of SAOZ is to collect informations on the column densities of several molecular species (ozone, nitrogen, water vapor) in the atmosphere.

The spectra acquired by the spectrometers can also be used to analyze the radiation field at the balloon's place, in the visible wavelength domain.

In this paper we consider a sequence of spectra covering a sunset in May 2002 (section 2). Fits of the spectra will be used to analyze the extinction of sunlight through successive, and thicker, layers of the atmosphere (sections 3 and 4), to derive a general analytical expression for the radiation field in the atmosphere. This will further help in understanding what the radiation field transmitted through a clear atmosphere, by a background source of light (as the sun), should be.

The pertinence of these conclusions, reached through the sole analysis of extinguished sunlight spectra, can be verified -because of the proximity of the sun, and of our knowledge of the atmosphere- giving weight to the idea that a formal, and model-independent study of spectra can lead to necessary conclusions on the nature of the media crossed by light (precisely; on the particles which compose these media).

In section 4.5 we discuss possible applications of this work in a fundamental problem of ground-based astronomy: the correction for atmospheric extinction.

## 2 data

### 2.1 Instrument

Up until recently, the balloon-borne SAOZ instrument consisted of a lightweight solar occultation spectrometer, in which, the solar tracker is a conical mirror defining a field of view of  $[-5^\circ, +10^\circ]$  elevation and  $360^\circ$  azimuth (see Pommereau et al. (1991); Pommereau & Piquard (1994); Goutail et al. (2001) for a complete description; some informations on SAOZ are also available at: <http://www.aero.jussieu.fr/themes/CA/>). This instrument performs measurements from  $3000 \text{ \AA}$  to  $6000 \text{ \AA}$ .

In this standard configuration, SAOZ is used to measure the stratospheric column densities -between the sun and the balloon- of ozone and nitrogen.

Table 1  
Parameters for the spectra used in the article

n°	U.T.=L.T.-2h			SZA <sup>(1)</sup> °	Tg. Alt. <sup>(2)</sup> m	$N_{O_3}$ <sup>(3)</sup> $\text{cm}^{-2}$	$c_1$ <sup>(4)</sup>	Fit		
	h.	min.	sec.					$c_2$ <sup>(5)</sup>	$c_3$ <sup>(5)</sup>	$c_4$ <sup>(5)</sup>
1	19	08	51	89.69	29094.5	$9.35 \cdot 10^{18} \pm 8 \cdot 10^{16}$	1.0	0.0005	0.00	0.000
2	19	18	6	91.20	27553.2	$8.22 \cdot 10^{19} \pm 3 \cdot 10^{17}$	1.0	0.0075	0.00	0.000
3	19	27	14	92.68	22355.4	$2.23 \cdot 10^{20} \pm 6 \cdot 10^{17}$	1.0	0.029	0.00	0.000
4	19	34	56	93.91	15930.8	$2.62 \cdot 10^{20} \pm 7 \cdot 10^{17}$	1.5	0.094	0.00	0.004
5	19	38	56	94.53	12437.2	$2.16 \cdot 10^{20} \pm 3 \cdot 10^{18}$	3.5	0.16	0.00	0.003
6	19	39	43	94.66	11654.8	$2.23 \cdot 10^{20} \pm 4 \cdot 10^{18}$	5.3	0.165	0.00	0.005
7	19	40	44	94.82	10696.8	$3.12 \cdot 10^{20} \pm 1 \cdot 10^{19}$	13	0.17	0.60	0.068
8	19	47	31	95.86	4776.1	$3.72 \cdot 10^{20} \pm 2 \cdot 10^{20}$	5	0.5	1.04	0.021
9	19	51	46	96.51	-	$\sim 3.35 \cdot 10^{20}$	100	0.4	1.40	1.933
10	19	58	46	97.56	-	$\sim 3.00 \cdot 10^{20}$	250	0.5	1.03	0.829
11	20	02	27	98.10	-	$\sim 4.00 \cdot 10^{20}$	800	Inf	1.35	-

- 1 Zenital angle of the sun.
- 2 Tangent altitude of the trajectory of sunrays, calculated from the respective positions of the balloon and of the sun. The calculation takes into account the bending of sunrays in the atmosphere.
- 3 Ozone column density with observational error margin. For the last three spectra we have no reliable observational measure of the column density (see text):  $N_{O_3}$  was estimated by hand from the spectra themselves. No error estimate on  $N_{O_3}$  is given for these spectra.
- 4 Scaling factor used in the figures, for each spectrum.
- 5 The fit of the spectra are proportional to:  $(e^{-c_2/\lambda^4} + c_4\lambda^{-1})e^{-c_3/\lambda}$

The ozone measure is precise to more than 5 % if the light received by the receptor in the ozone wavelength range is direct sunlight alone. When the sun is low in the horizon direct sunlight diminishes and the receptor, because of its' large azimuthal aperture, receives a large amount of scattered sunlight from different directions; in this case the ozone measure becomes meaningless. The relative contribution of scattered light to the radiation field at the balloon location is monitored by means of the color index.

Pressure, temperature and GPS (Global Positioning System) altitude and location are also measured on-board with an accuracy of respectively 1 hPa,

0.5 °K and 100 m.

A new spectrometer is now added to the experiment to measure water vapor in the stratosphere. This spectrometer covers the  $[0.4\,\mu\text{m}, 1\,\mu\text{m}]$  wavelength domain with a resolution of 6.33 Å.

## 2.2 Data

The spectra presented in the paper come from the first test-flight with the new spectrometer. SAOZ was launched from Aire sur Adour (Landes, France) on May 14, 2002, and stabilized (to within 50 m during the flight) at an altitude of  $\sim 28900$  m.

Spectra were alternatively taken by each spectrometer, at an average rate of one spectrum per 50 seconds. The old spectrometer is used to determine the column density of ozone. For studying the radiation field at the balloon's location, we used data from the new spectrometer, because of its larger wavelength coverage.

We used the observations from a sun at zenithal angle  $SZA = 89.7$  (the sun is observed through a thin stratospheric layer), to  $SZA = 98.1$  (i.e. the sun is below the horizon).

## 2.3 Ozone correction

The broad-band ozone absorption occupies the central part of the spectra, between  $\sim 5000$  Å and  $\sim 7000$  Å. The wavelength dependent absorption cross section of ozone,  $\sigma_\lambda$ , is plotted in Figure 1. To correct a spectrum for the absorption by ozone, the spectrum needs to be multiplied by  $e^{\sigma_\lambda N_{O_3}}$ , with  $N_{O_3}$  the column density of ozone.

## 2.4 Table 1

Table 1 summarises the informations on the spectra.

The first and second columns are the number given to each spectrum and the universal time of the observation (local time=U.T.+02h).

Columns 3 and 4 are the angular distance of the sun to the zenith (SZA), and the tangent altitude of the average trajectories of sunrays. The latter takes into account the bending of sunrays due to the variations of the refractive

index of the atmosphere. It is used to define the different layers crossed by sunlight in the atmosphere.

The  $N_{O_3}$  column is the ozone column density for spectrum (1), to spectrum (7), measured by the old spectrometer (section 2.1). The error on  $N_{O_3}$  increases with time due to the setting of the sun and the growing importance of scattered sunlight. For the four last spectra  $N_{O_3}$  was estimated from the best correction applied to the spectra to reduce, or suppress, the ozone depression (section 3).

The last four columns are the parameters we found for the fits of the spectra.

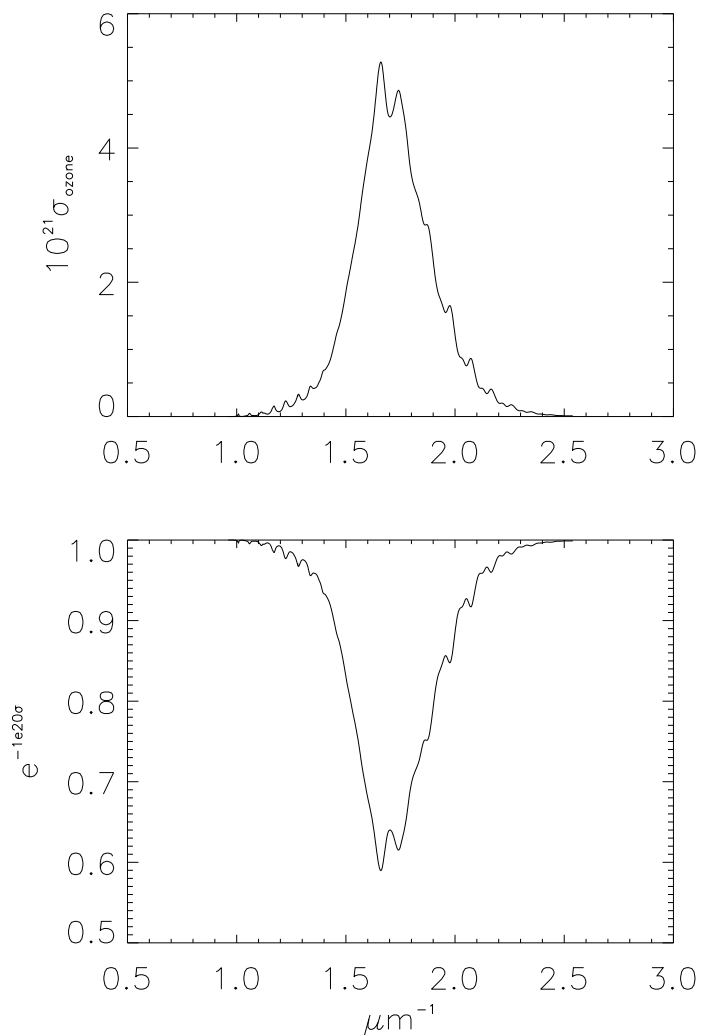


Fig. 1. *Top*: profile of the ozone absorption cross-section. *Bottom*: ozone absorption for an ozone column density of  $N_{O_3} = 10^{20} \text{ cm}^{-2}$ .

### 3 Analysis

The following sections analyze the sequence of decreasing sunlight spectra from a sun above the atmosphere, to the complete extinction of sunlight below the horizon. We distinguish four periods. For each of these periods we have extracted a few representative spectra. All the spectra are normalized by a spectrum of the sun at  $19^h03^m43^s$ , when the sun is still observed above the atmosphere. The spectra are scaled to 1 in the near-infrared ( $\lambda \sim 9500 \text{ \AA}$ ). The scaling factor is  $c_1$ , sixth column of Table 1.

#### 3.1 Direct sunlight alone (figure 2)

Top of Figure 2 is a plot of the first normalised spectra of the sunset against wavelength. While the balloon had, a few minutes ago, been observing the sun above the atmosphere, sunrays now cross the upper atmospheric layer, the stratosphere.

The large absorption band between  $5000 \text{ \AA}$  and  $7000 \text{ \AA}$  is due to ozone (the Chappuis visible bands). Ozone absorption increases with time, with the increase of optical path followed by sunrays through the stratosphere.

The middle plot of the figure reproduces the spectra of the upper plot (plain lines), as a function of wave-number. The dotted lines are the same spectra after correction for  $O_3$  absorption (see section 2.3).

The spectra corrected for the broad-band ozone absorption all decrease as an exponential of  $1/\lambda^4$  (bottom plot of figure 2). We conclude that extinction through the stratosphere is of Rayleigh type, due to the stratospheric gas (nitrogen essentially).

#### 3.2 Direct sunlight and low optical depth scattered sunlight (figure 3)

From  $\sim 19^h34^m$  on (between spectra (3) and (4)), the spectra can no longer be fitted by the Rayleigh extinction alone. As illustrated by spectrum (4) (figure 3, bottom plot), the  $e^{-c_2/\lambda^4}$  fit still holds for the shortest wave-numbers but, towards the UV, the spectra have larger values than expected. The reason for this excess is the addition of a component of scattered sunlight which appears with the increase of extinction. As expected, scattered light is first detected towards the UV, where extinction is the highest.

The scattered light behaves as  $\lambda^{-1}$  (figure 3, bottom), not as  $\lambda^{-4}$  as it would

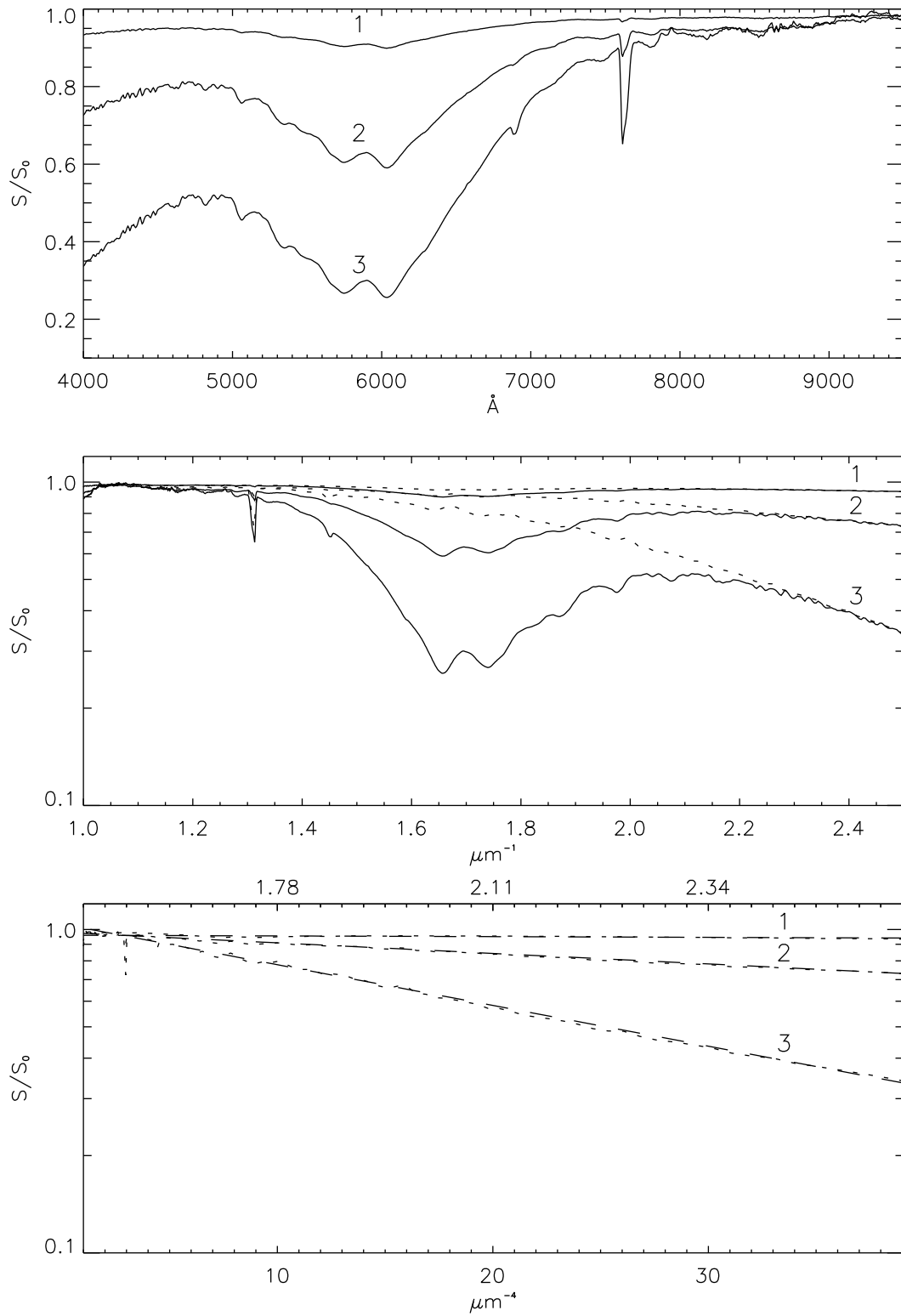


Fig. 2. First spectra of the sun observed through the stratosphere. Spectra are labeled by their number in Table 1. *Top:* the spectra are divided by the spectrum of the sun and are scaled to 1 in the near-infrared, x-axis in  $\text{\AA}$ . *Middle:* same spectra but presented against  $1/\lambda$ , and with the correction for absorption by ozone (in dots). *Bottom:* the spectra (in dots) corrected for ozone extinction decrease exponentially as  $1/\lambda^4$  (exponential fit in dashes). The bottom x-axis is  $1/\lambda^4$ .  $1/\lambda$  is represented on the top x-axis of the plot.

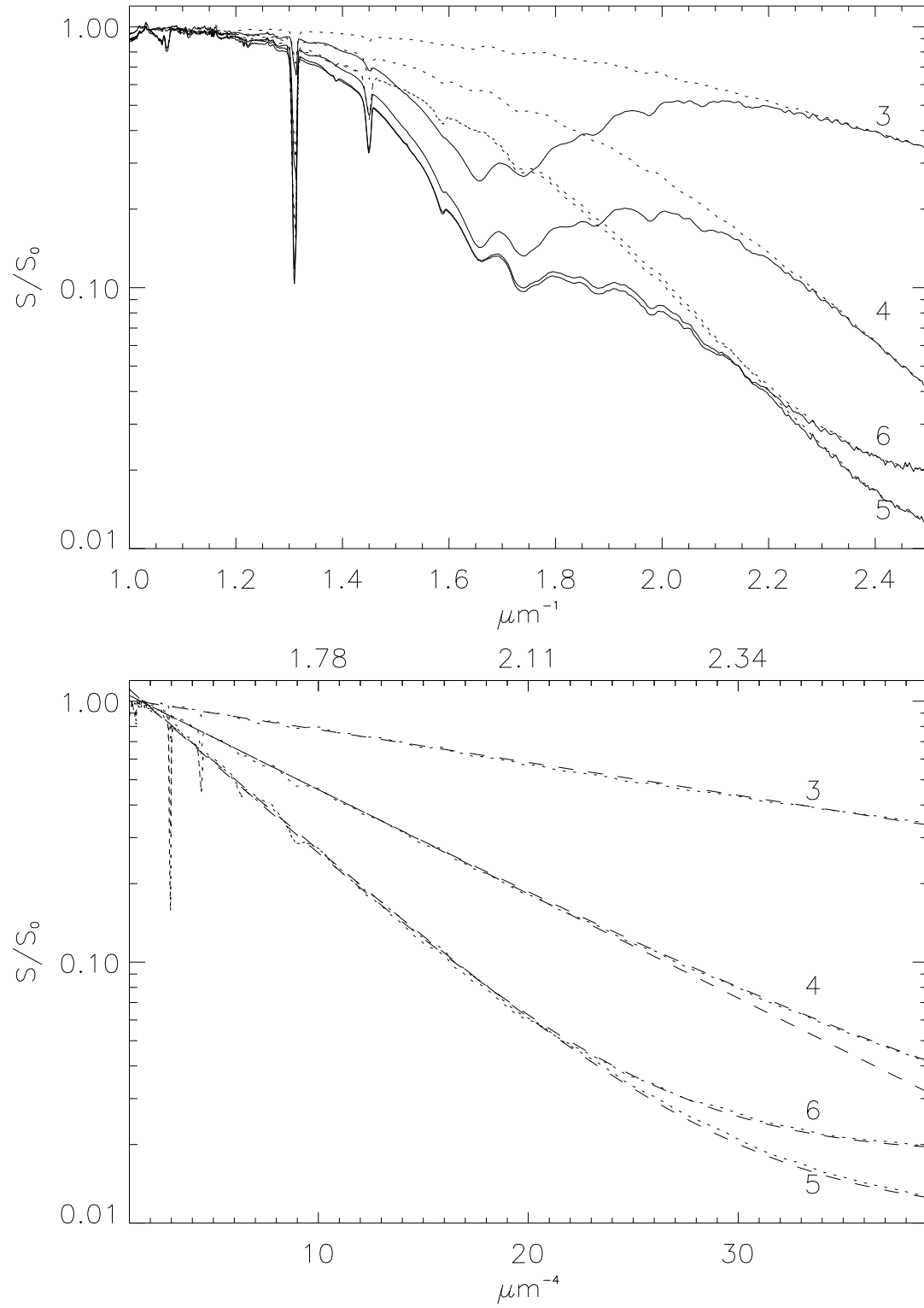


Fig. 3. Spectrum (3) from figure 2, and spectra (4) and (5) (Table 1). Original spectra are in solid lines, spectra corrected for ozone absorption in dots, fits in dashes. *Bottom:* The  $1/\lambda^4$  gas extinction increases with time. Towards the UV, this extinction is no longer enough to fit the spectra (see spectrum (4)). The exact fits comprise an additional term,  $\propto \lambda^{-1}$ , corresponding to low optical depth scattering of sunlight by aerosols in the troposphere.



if scattering was due to molecules. We know from scattering theory that the particles, atmospheric aerosols in the present case, must be large compared with the wavelength.

The normalized spectra corrected for ozone absorption are now the sum of a direct sunlight component,  $\propto e^{-c_2/\lambda^4}$ , and a scattered sunlight component,  $\propto \lambda^{-1}$ . We observe the short-wavenumber rise of scattering: the  $\lambda^{-1}$  dependence of the scattered sunlight corresponds to the small optical depth approximation.

Spectra (5) and (6) have nearly the same gas extinction while the scattered components are clearly separated, meaning that gas extinction and aerosols scattering are not necessarily dependent.

The detection of a small column density of aerosols on the path of sunrays indicates that sunlight now crosses the upper part of the troposphere. This is confirmed by the independent information on the relative position of the balloon and of the sun.

### *3.3 Increased importance of the scattered sunlight (figure 4)*

After 19<sup>h</sup>:40<sup>m</sup> the small optical depth approximation no longer holds in the observational wavelength range. Scattered sunlight is now fitted by a more general function  $\propto \lambda^{-1} e^{-c_3/\lambda}$ , expected for forward scattering (Zagury, 2003b).

Direct sunlight rapidly decreases. The main cause of direct sunlight extinction is still the  $e^{-c_2/\lambda^4}$  Rayleigh extinction. The extinction of direct sunlight by aerosols is comparatively negligible ( $c_3/\lambda \ll c_2/\lambda^4$ ).

Observational determination of ozone column density becomes meaningless with the increase of scattered sunlight (section 2.1). For spectrum (8), scattered light occupies the whole spectrum for  $1/\lambda > 1.7 \mu\text{m}^{-1}$ , and the ozone correction had to be adjusted by hand.

Scattered light progressively replaces direct sunlight as the sun sets.

### *3.4 Scattered sunlight (figure 5)*

When the sun disappears below the horizon scattered light occupies all the spectrum except for its nearest infrared part. Replacement of direct sunlight by scattered light is accompanied by an important diminution of the overall intensity of the radiation field (2-3 orders of magnitude, column  $c_1$  in Table 1).

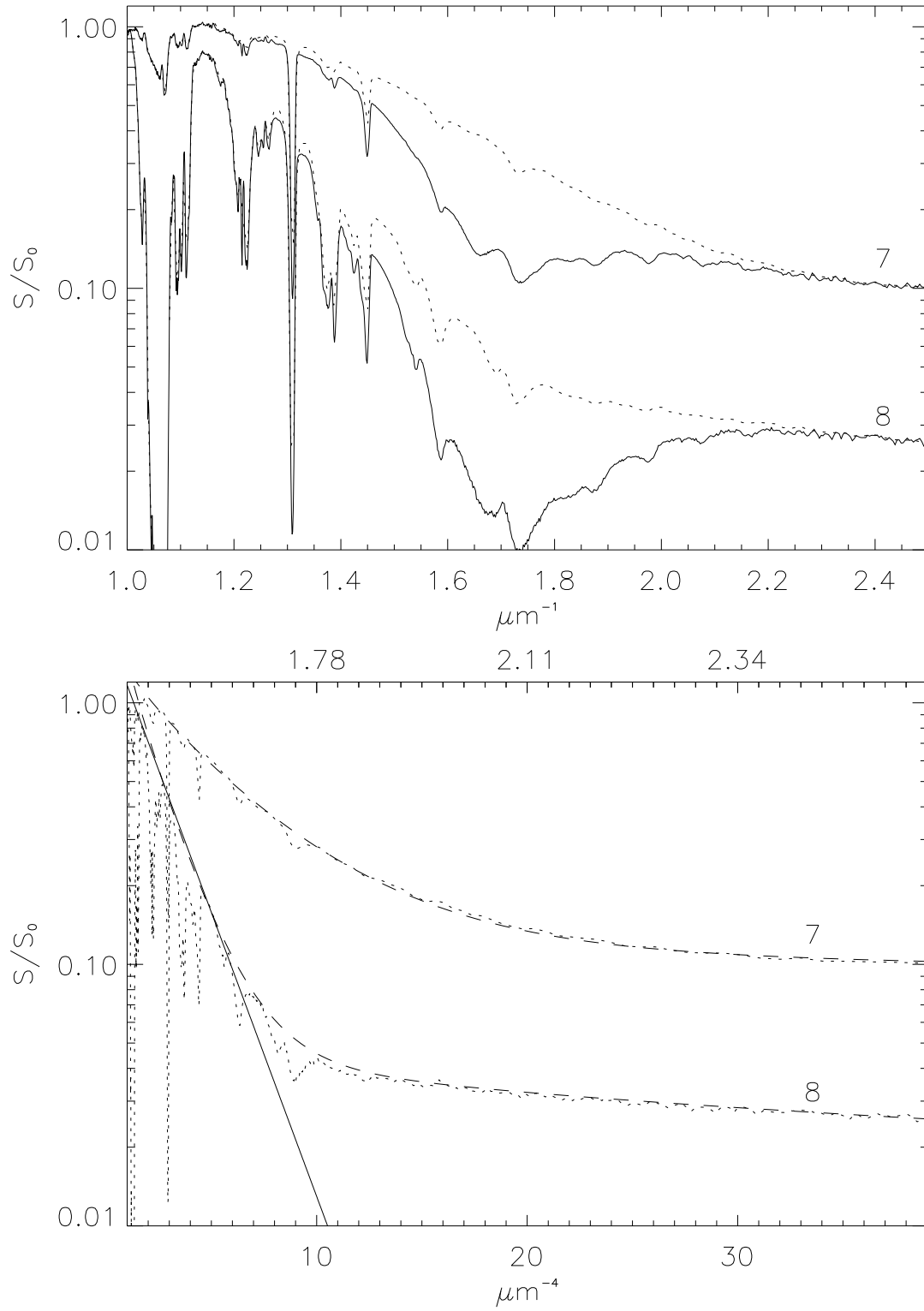


Fig. 4. Original spectra are in solid line, spectra corrected for ozone absorption in dots, fits in dashes. *Top*: For spectrum (8), the ozone correction is less precise than in the preceding spectra, probably due to the increased importance of the scattered light. *Bottom*: Fit of the spectra with a direct sunlight component and a scattered light component  $\propto \lambda^{-1} e^{-c_3/\lambda}$ . Direct sunlight extinction is nearly all extinction by the gas,  $e^{-c_2/\lambda^4}$ .

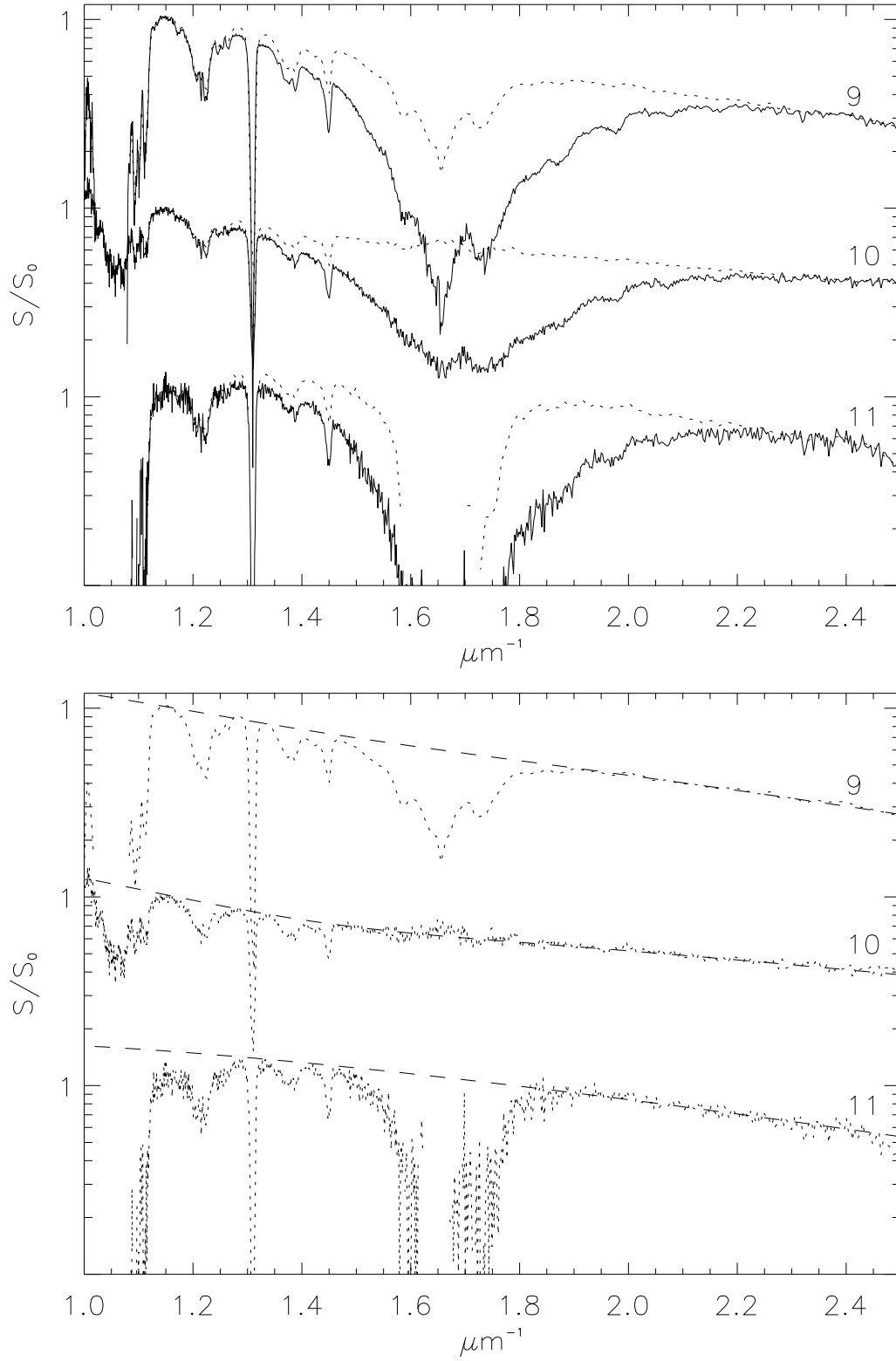


Fig. 5. Original spectra are in solid line, spectra corrected for ozone absorption in dots, fits in dashes. Direct sunlight is rejected to the near-infrared. Compared to daylight the radiation field diminishes by 2-3 orders of magnitude (column  $c_1$  in Table 1). Correction for ozone absorption was adjusted by hand and could not be achieved for spectra (9) and (11).

Table 2

Analytical expressions of the fits used in Figure 6

n° (1)	spectrum (2)	Fit (3)
a	3	$e^{-8 \cdot 10^{19} \sigma_{\lambda}} e^{-0.029/\lambda^4}$
b	5	$0.4 e^{-2 \cdot 10^{20} \sigma_{\lambda}} (e^{-0.16/\lambda^4} + 3 \cdot 10^{-3}/\lambda)$
c	7	$0.2 e^{-2 \cdot 10^{20} \sigma_{\lambda}} (e^{-0.17/\lambda^4} + 7 \cdot 10^{-2}/\lambda) e^{-0.6/\lambda}$
d	10	$0.01 e^{-3 \cdot 10^{20} \sigma_{\lambda}} (e^{-0.5/\lambda^4} + 0.8/\lambda) e^{-1.03/\lambda}$

- 1 Letters refers to the curves of Figure 6.
- 2 Number of the spectrum in Table 1.
- 3  $\sigma_{\lambda}$  is the ozone absorption cross-section.

We tried to determine an average  $N_{O_3}$  by correcting the ozone deficit feature of each spectrum. The correction found for spectrum (10) leads to  $N_{O_3} = 3 \cdot 10^{20} \text{ cm}^{-2}$ . The ozone absorption feature in spectra (9) and (11) is much deeper than in any of the previous spectrum. The correction was limited to the wings of the absorption band. A larger correction introduces a bump-like feature which is not coherent with the rest of the observations. We explain the difficulty to correct better these spectra by the low level in the Chappuis bands, below the limit of sensitivity of the detector.

## 4 Discussion

### 4.1 Interpretation of the fits

The conclusions reached from the discussion of the spectra (section 3) agree with the observational indications in our possession, the position of the sun which determines the optical path of sunrays in the atmosphere, the color index which confirms the presence of scattered light and measures its importance.

The intensity of the radiation field at any point of the atmosphere, before complete darkness, and in good atmospheric conditions (no heavy clouds), normalized by the spectrum of the sun, should be represented by one of the functions of Table 2 (constants in these functions should be considered as orders of magnitudes), and illustrated by Figure 6.

The spectra choosen for Figure 6 are the fit of spectra (3), (5), (7) and (10).

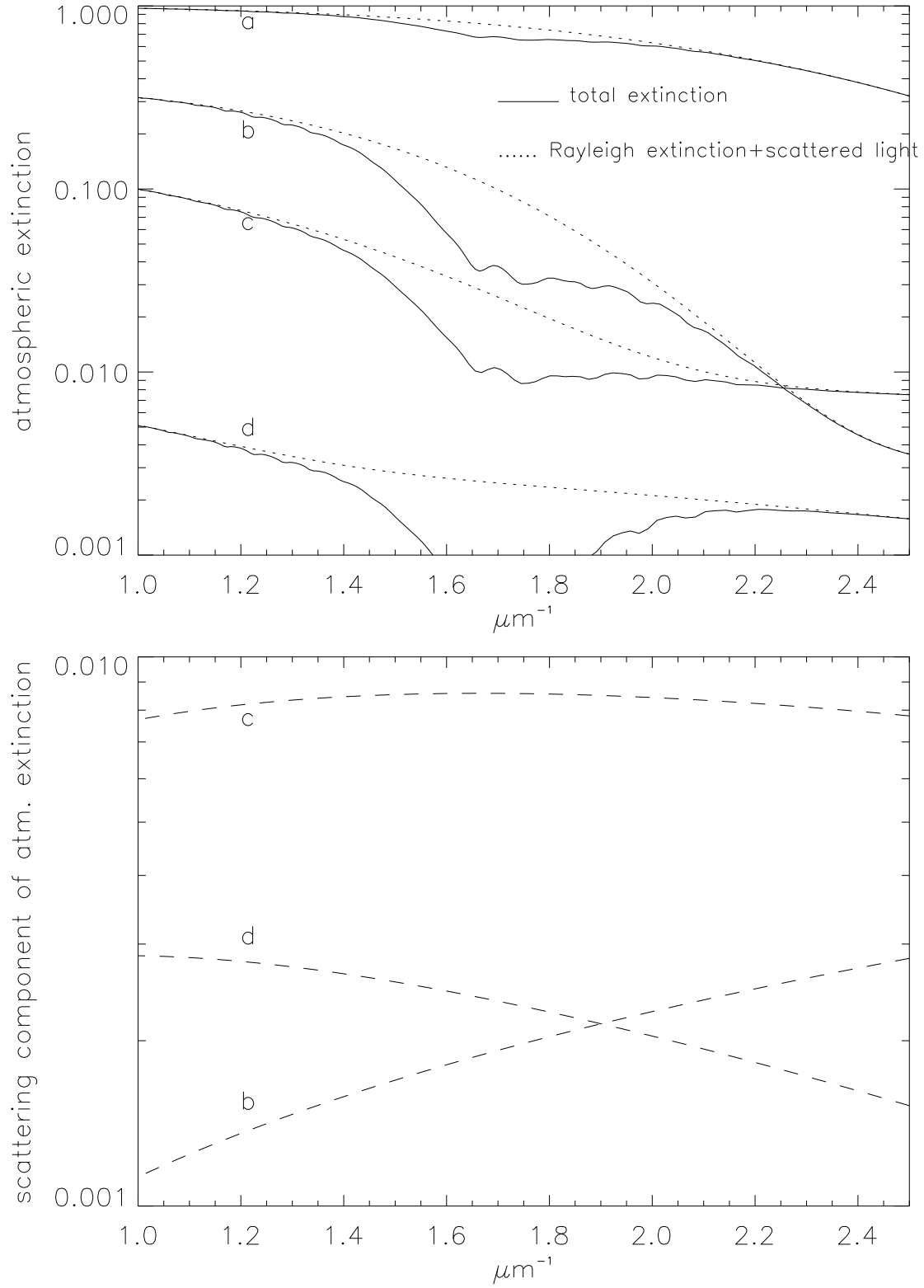


Fig. 6. The four steps in atmospheric extinction (*top*) and the forward scattering component alone (*bottom*): (a)=gas extinction alone, (b)=gas extinction+ rising scattered light, (c)=gas extinction+ second order scattered light, (d)=scattered light alone. The analytical formulae are given in Table 2, and discussed in section 4.1.

Curve (a) is extinction by the gas alone. The dotted line is the spectrum corrected for ozone absorption, and fits the  $1/\lambda^4$  Rayleigh gas extinction. Curve (b) is gas extinction plus the low optical depth rise of scattered light by aerosols. In curve (c), the scattered component is displaced towards the longest wavelengths, and is perceived over all the visible spectrum. The intensity of the scattered light does not vary much throughout the spectrum, because the maximum is reached at  $1/\lambda \sim 1.65 \mu\text{m}^{-1}$  ( $\lambda \sim 6000 \text{ \AA}$ ). In spectrum (d), direct sunlight is a minor component of the radiation field; the maximum of the scattered light has moved to the infrared.

In addition to the extinction of sunlight, there is a progressive diminution of the radiation field corresponding to the constant factor in front of each fit of Table 2. This is because of the sunset, only the upper (and decreasing with time) part of the sun participates to the radiation field at the cloud location. This also explains why the normalized intensity of the maximum of the scattered light of spectrum (d) is diminished compared to spectra (c) (bottom plot of Figure 6).

The general form of the normalised radiation field measured at the balloon location is:  $\propto (e^{-c_2/\lambda^4} + c_4/\lambda)e^{-c_3/\lambda}$ . It is not:  $\propto (1 + c_4/\lambda)e^{-c_3/\lambda}e^{-c_2/\lambda^4}$ . Which means that, scattered sunlight by aerosols behaves as if it was not extinguished by the gas. No satisfying reason can yet be advanced to understand this particularity.

#### 4.2 *The radiation field in the earth's atmosphere*

The four steps described in section 3 correspond to a sun hidden behind successive, and thicker layers of the atmosphere. Although the detector receives the light from all directions, the radiation field is (within the sensitivity of the instrument), all direct sunlight, and forward scattered light by aerosols: the radiation field at the receptor location is dominated by light coming from the direction of the sun. Due to the efficiency of forward scattering by aerosols, the radiation field in the atmosphere is still, at the time the sun disappears below the horizon, oriented by the direction of the sun.

In the stratosphere, extinction is of Rayleigh type (regardless of the absorption bands), most of which must be due to nitrogen (80% of the gas). The light scattered by the gas in the stratosphere and in the troposphere, and received by the detector, should vary as  $\propto \lambda^{-4} e^{-a/\lambda^4}$  (Rayleigh, 1871). It is weak compared to direct sunlight since it is not detected; isotropic scattering, although it comes from a much larger angle, is much less efficient than forward scattering.

The time scale for noticeable variations in the spectrum of the radiation field is of order of a minute (Table 1).

### 4.3 *The atmosphere viewed from earth*

On earth, an observer looking in a different direction from the sun receives the light scattered by particles in the atmosphere. If the direction of observation is far enough from the sun, forward scattering is not efficient, because the angle of scattering is large. The light received by the observer must be light isotropically scattered by molecules in the atmosphere. If the radiation field in the atmosphere is homogenous enough along the direction of observation, the spectrum of the light received on earth, normalised by the spectrum of the sun, must be proportional to  $1/\lambda^4$  times one of the spectra of Figure 6.

### 4.4 *Extinction theory*

The analysis given so far was based on the simple principles of the extinction theory. Ozone absorption aside, the size of the particles is the determining parameter to understand the spectrum of a sunset, regardless of the particular composition of the particles present in the atmosphere.

From the analytical fits of the spectra (Figure 6) direct sunlight, and forward scattered sunlight can be separated. The intensity of the scattered light, integrated over all directions, is (bottom plot of Figure 6) between 1% and 5% (if we scale the constant factor of fit ( $c$ ) to 1) of the direct sunlight corrected for extinction. This value is of the same order as the one estimated in Zagury (2001) for interstellar grains.

### 4.5 *Application to observations in astronomy*

An object observed through the atmosphere should be extinguished in the same way as sunlight is. Since the light received from a far away object crosses both the stratosphere and the troposphere, the applied correction should have one of the general expression (b), (c), or (d), of Table 2.

The proportion of molecular and aerosol extinctions along the line of sight is a crucial point to determine how far towards the infrared atmospheric extinction will be felt. In thin atmospheres, the effect of aerosols under  $1/\lambda = 2 \mu\text{m}^{-1}$  ( $\lambda \geq 5000 \text{ \AA}$ ) should be negligible. If the ozone column density is larger than  $10^{19} \text{ cm}^{-2}$ , the shape of the spectrum can be modified substantially in the visible portion of the spectra, from  $1/\lambda = 1.5 \mu\text{m}^{-1}$  to  $1/\lambda = 2.1 \mu\text{m}^{-1}$  ( $5000 \text{ \AA} \leq \lambda \leq 7000 \text{ \AA}$ ).

The beam of ground-based telescopes is much smaller (e.g. less than a few

arcsecond) than the field of view of SAOZ's conical mirror. Therefore, depending on the phase function of aerosols, the importance of scattered light (the  $1/\lambda$  term) may be reduced. If the stratospheric layer is of low optical depth, or can be considered constant between the direction of observation and the direction of the reference object used to calibrate the spectra, gas extinction (the  $e^{-c_2/\lambda^4}$  term) tends to vanish; the  $e^{-c_3/\lambda}$  aerosol extinction term is the only one to remain. In this case, only the slope of the spectrum is modified.

The time-scale deduced from Table 1 for noticeable variations of the atmospheric extinction (due to the rotation of earth) is of order one minute. If the duration of the observation is of a few minutes or more, the correction for atmospheric extinction may have a more complicated analytical form than the simple functions of Table 2. In this case, it is not evident that atmospheric extinction can easily be removed. Spectral observations of nebulae, which generally require a few minutes observing time, are first concerned.

Contamination by direct starlight scattered in the atmosphere is another source of uncertainty for spectral observations of nebulae. Since forward scattering is governed by the angle of scattering and the number of scatterers, rather than by the distance (source of illumination)-(scattering medium) (Zagury, 2003a), there may be a competition between the light scattered by the nebula and the light scattered in the atmosphere. This effect can be estimated in several ways: through the comparison of aerosols and nebular column densities, and by observing a non-reddened star similar to the star illuminating the nebula. The effect of atmospheric extinction on astronomical spectral observations, can also be investigated by observing the same objects at different air-masses, and on different days.

## 5 Conclusion

The observation of a sunset by the SAOZ balloon experience has produced a succession of spectra of the radiation field at the balloon location. We have isolated four characteristic kinds of spectra from this sequence, which we have fitted and analyzed. The physical interpretation of each fit is in good agreement with the independent information in our possession on the path followed by sunrays through the atmosphere, between the sun and the balloon.

Our first task in this analysis was to correct the spectra for the ozone absorption. The corrected spectra are then analyzed as follows.

When the sun is observed through the stratospheric layer only, sunlight is attenuated by a factor  $e^{-c_2/\lambda^4}$ : atmospheric extinction is mainly Rayleigh scattering by the gas (nitrogen essentially).



Coinciding with the entrance of sunrays into the troposphere, gas extinction is no longer enough to fit the spectra towards the UV. A  $c_4/\lambda$  term must be added. This term corresponds to forward scattering of sunlight by large particles (aerosols) in the troposphere.

On increasing the optical depth, both gas and aerosols extinctions increase. Extinction by aerosols now introduces a  $e^{-c_3/\lambda}$  term which affects scattered light and -but to a lesser extent- direct sunlight. Scattered light increases when the sun reaches the horizon; and is progressively perceived towards the larger wavelengths.

When the sun is below the horizon, just before complete darkness, forward scattered light dominates the whole visible spectrum.

We deduce that in daylight, and during sunset, most of the light received at the balloon location, and similarly at any point of the atmosphere, comes from the direction of the sun. This radiation field is then the sum of two effects on sunlight. One effect is extinction of the direct sunlight, mainly due to the gas. This includes the broadband ozone absorption, and Rayleigh extinction by the gas with an extinction optical depth  $\propto \lambda^{-4}$ . This direct and extinguished sunlight component of the radiation field is the only one to consider if sunrays cross the stratosphere alone. The second component of the radiation field is forward scattered sunlight by aerosols in the troposphere. The spectrum of the forward scattered light by aerosols is well fitted by a function  $\propto \lambda^{-1}e^{-c_3/\lambda}$ . Sunlight scattered by aerosols progressively replaces direct extinguished sunlight at sunset, with an important diminution of the intensity of the radiation field. Scattered sunlight is at most a few percent of non-extinguished direct sunlight.

The spectrum of the light received at the earth's surface from a direction far enough from the sun should be proportional to  $1/\lambda^4$  times the spectrum of the atmosphere on the line of sight (section 4.3).

Our analysis made use of the general principles of scattering theory, and did not require the use of any model. We show that, without calling to deterministic models of the atmosphere, it is possible to understand, separate, and quantify the components of the radiation field, direct and scattered sunlights.

Since starlight should be extinguished by the atmosphere as sunlight is, we have (section 4.5) discussed applications of this work to ground-based observations in astronomy.

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